VISIT…

7
Alkylated Aromatics

Margaret M. Wu
Mobil Technology Company
Paulsboro, New Jersey

Since the review of alkylated aromatics in the first edition of *Synthetic Lubricants and High Performance Functional Fluids* [1], there have been numerous developments in fluid production, commercial applications, and basic understanding of this class of fluids. In this chapter, we summarize these new developments together with the key points discussed in the first edition to provide a comprehensive review of the subject

I. INTRODUCTION

Alkylated aromatics, containing aromatic and aliphatic components in the same molecule, are well known to be present in the petroleum-derived, mineral-based stock. They provide excellent lubricant function and are usually described as the "aromatic content" in lube oil.

Alkylated aromatics as lubricant base stocks were first developed in Germany during World War II [2]. These early developments were primarily motivated by a shortage of petroleum-derived base stock, not by any performance advantage offered by these fluids. Therefore, as soon as petroleum-based fluid became available, the push to develop the alkylated aromatics quickly disappeared.

During the late 1960s and early 1970s, engine oils formulated with Conoco alkylbenzene fluids were used by the construction crews on the trans-Alaska pipeline project because of the excellent low temperature rheological properties of the lubricants [3]. In this application, the advantages of the alkylbenzene fluids were clearly defined: better low temperature properties, better lubricity, lower oil consumption, and improved fuel economy. However, after the completion of Alyeska Pipeline, the use of this type of fluid failed to grow. In the subsequent years, alkylbenzene fluids were never commercialized in large quantity, probably because they were by-products of the detergent alkylate process. In recent years, both fluid producers and lubricant formulators reported numerous activities in developing alkyl aromatic fluids for use in industrial or engine lubricants. Factors contributing to these activities are as follows:

Unique performance advantages for many alkylated aromatics were clearly identified for special applications.

Copyright © 1999 Marcel Dekker, Inc.

Extensive new developments in alkylation technology have improved the quality and supply of alkyl aromatics.
Alkylated aromatics can be produced from readily available raw materials at reasonable cost.

As a result, alkyl aromatic fluids have reemerged as cost-competitive, high performance base stocks.

The term "alkylated aromatics" covers a wide range of fluids. Depending on the selection of the aromatic component, their properties vary widely, from oils with excellent viscometric properties, such as alkylbenzenes, to oils with superior thermal and oxidative stabilities, such as sulfur-containing alkylated aromatics. This chapter organizes the alkylated aromatics into three classes of fluids according to the aromatic component:

1. Alkylbenzenes
2. Alkylnaphthalenes
3. Alkylated aromatics containing heteroatoms

The production, properties, and applications of these fluids are reviewed in the following sections.

II. CHEMISTRY: SYNTHESIS AND PRODUCT STRUCTURES

A. General

1. Reagents

Most alkylated aromatic fluids are produced from well-known chemistry, the Friedel–Crafts alkylation of aromatic compounds [4]. In this reaction, an aromatic compound, such as benzene, naphthalene, or its substituted analogue, is alkylated by an olefin, alkyl halide, or alcohol over a Friedel–Crafts catalyst [5]. Olefins are the most often used among these alkylating reagents because they are readily available at low cost and generate no by-products upon alkylation. In contrast, an alkyl halide or alcohol would generate hydrogen halide or water as by-products. The olefins can be either α-olefins, internal olefins, or branched olefins with 8 to 18 carbons in the molecule. These large olefins are used because they produce alkylated aromatics with at least 25 carbons and with molecular weight greater than 300. Alkyl aromatics of this range derived from benzene, naphthalene, or other aromatics have low volatilities and good viscometric properties as lubricant base stocks. Lighter alkyl aromatics of 15 to 20 carbons are used in special applications, such as refrigeration fluids and insulating oils.

2. Catalysts

Many homogeneous [4,5] or heterogeneous solid catalysts [6] are used to catalyze the alkylation of aromatic compounds. The catalyst and reaction conditions chosen depend on several factors, including substrate reactivity and alkylate quality requirements. For example, strong acids, such as $AlCl_3$, BF_3, or HF are used to alkylate benzene, which has a relatively low alkylation reactivity. Milder Friedel–Crafts catalysts, such as $FeCl_3$ or $SnCl_4$, were claimed to be effective for the alkylation of highly reactive aromatics, such as *o*-xylenes or naphthalene. These halide-containing homogeneous catalysts are usually corrosive and generate undesirable waste at the end of the reaction. Newer alkylation technology employs solid, heterogeneous catalysts, especially zeolites [7] or solid superacids [8]. Solid catalysts usually are noncorrosive, and many can be regenerated and reused. In addition to this process advantage, zeolites produce alkyl aromatics with unique isomer distributions that may contribute to unexpected performance advantages over products from conventional catalysts. The use of special catalysts or reaction conditions to favor the formation of specific isomer or monoalkylates to give optimized lubricat-

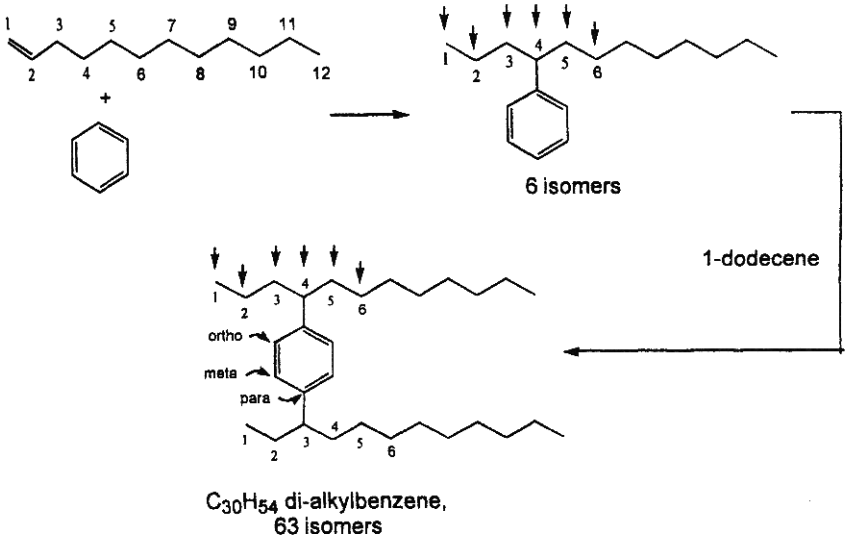
Copyright © 1999 Marcel Dekker, Inc.

ing properties has been widely reported. Examples of the synthesis of different alkylated aromatic fluids by using different catalysts are discussed later.

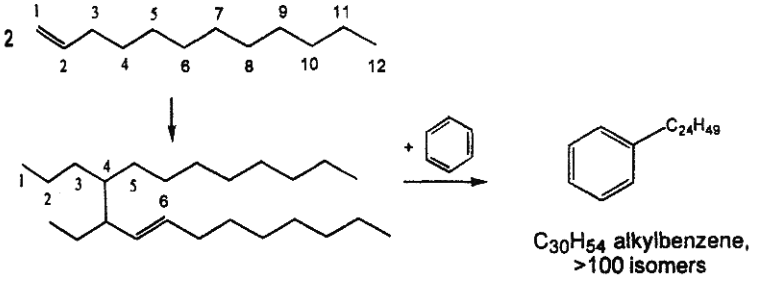
3. Product Compositions

Alkylated aromatics from Friedel–Crafts alkylation reactions usually have very complex chemical compositions with many possible isomers. This complexity can be illustrated by the possible isomeric structures for a $C_{30}H_{54}$ didodecylbenzene from benzene and 1-dodecene. There are two different schemes to produce the dialkylbenzene. In the first reaction sequence, the monoal-kylbenzene further reacts with the second olefin to give didodecylbenzene (Eq. 1). In this dialkylbenzene molecule, the aromatic ring may connect to either one of the two alkyl chains at any one of the six possible positions, creating a total of 21 possible isomers. Furthermore, the two alkyl substitutents may occupy either the ortho, meta, or para position on the benzene ring. With these arrangements, 63 isomers are possible. Even discounting the unfavorable isomers, such as *o*-dialkylbenzene or 1-phenylalkane, we can easily have more than 30 possible isomers for this dialkylbenzene.

In another possible scheme to create the $C_{30}H_{54}$ alkylbenzene lube, two dodecenes first dimerize to give a C_{24} olefin, which then reacts with benzene to give a C_{30} monoalkylbenzene lube (Eq. 2). The C_{12} dimer can have 21 possible isomers, and each isomer may have many positional isomers for phenyl substitution. This results in an extremely complex mixture. If larger olefins are used as alkylating agents, more isomers are possible for the alkylbenzene products.



(eq. 1)



(eq. 2)

Copyright © 1999 Marcel Dekker, Inc.

Among all the possible compositions, some structures have better lubricating properties than others. Therefore, a better alkyl aromatic base stock can be produced by tailoring reaction conditions and/or alkylation catalysts to favor the production of these special compositions. Many patents deal with this aspect of the technology. These structure–property correlations are discussed later in connection with each class of alkylated aromatic fluids.

B. Alkylbenzenes (AB)

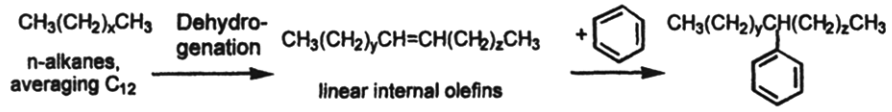
1. Commercial Processes

Commercial alkylbenzene fluids with 100°C kinematic viscosity of 2.5–10 cSt are available from detergent alkylate producers. Detergent alkylates, an intermediate for detergent manufacturing, are usually monoalkylbenzene. During the production of the detergent alkylate, some dialkylbenzene and heavier alkylbenzenes are also produced. These heavier alkylates, unsuitable as detergent alkylates, are excellent lubricant base stocks.

To discuss AB lubricant base stock manufacturing, we start with detergent alkylate manufacturing. There are two types of detergent alkylate: linear alkylbenzene (LAB) and branched alkylbenzene (BAB). Their production processes are summarized in Schemes 1 and 2 [9].

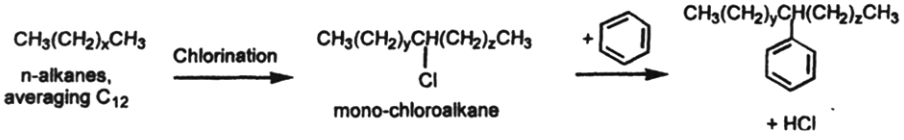
Scheme I. Linear Alkylbenzene (LAB) Production Scheme

(a) From n-paraffin dehydrogenation



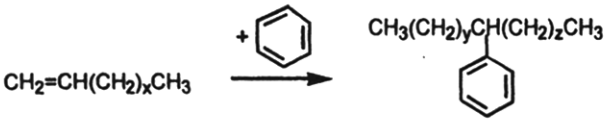
(eq. 3)

(b) From n-paraffin chlorination



(eq. 4)

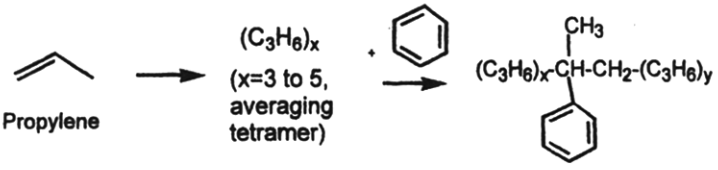
(c) From alpha-olefins



(eq. 5)

Scheme II. Branched Alkylbenzene (BAB) Production Scheme

(a) From propylene oligomers



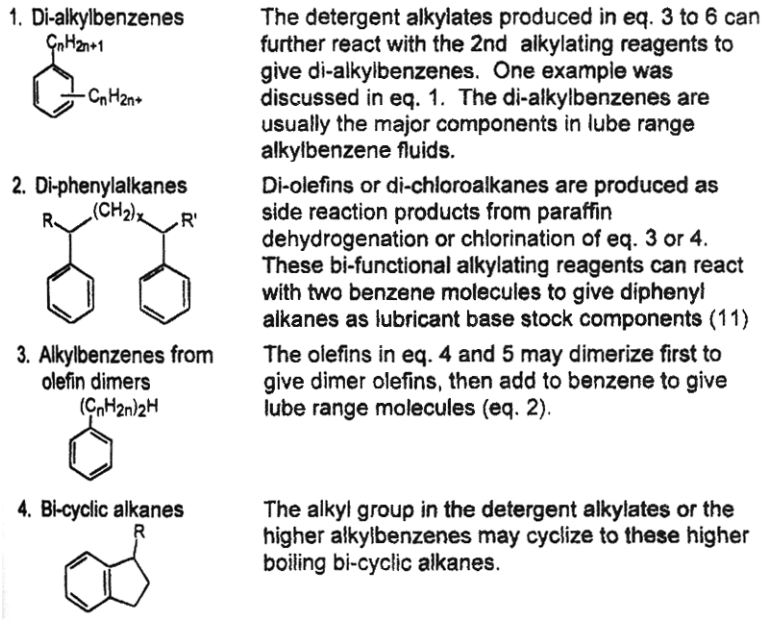
(eq. 6)

Copyright © 1999 Marcel Dekker, Inc.

The common feature of these processes (Eqs. 3–6) is that an alkylating agent is reacted with benzene over a Friedel–Crafts catalyst, such as HF, BF_3, $A1C1_3$ or zeolites. These processes differ in that each alkylating agent is produced by a different reaction. The alkylating agent can be either a linear internal olefin (Eq. 3), a monochloroalkane (Eq. 4), an α-olefin (Eq. 5), or a propylene oligomer (Eq. 6). The detergent alkylates produced in Eqs. 3–6 are C_{l6} to C_{22} alkylben-zenes with an average of 18 carbons per molecule. They are too light and too volatile for most lubricant applications, except in special cases such as refrigeration fluids.

The alkylbenzenes useful as synthetic lubricant base stocks are usually the heavier alkylbenzenes, which are produced from various side reactions in the detergent alkylate processes [10]. They usually amount to less than 10% of the total product. The chemical compositions of some of the heavier alkylates and the reactions that generate them are listed in Scheme 3.

Scheme III. Production scheme for heavier alkylates.


1. Di-alkylbenzenes
CnH2n+1
CnH2n+
The detergent alkylates produced in eq. 3 to 6 can further react with the 2nd alkylating reagents to give di-alkylbenzenes. One example was discussed in eq. 1. The di-alkylbenzenes are usually the major components in lube range alkylbenzene fluids.
2. Di-phenylalkanes
R
(CH2)x
R'
Di-olefins or di-chloroalkanes are produced as side reaction products from paraffin dehydrogenation or chlorination of eq. 3 or 4. These bi-functional alkylating reagents can react with two benzene molecules to give diphenyl alkanes as lubricant base stock components (11)
3. Alkylbenzenes from olefin dimers
(CnH2n)2H
The olefins in eq. 4 and 5 may dimerize first to give dimer olefins, then add to benzene to give lube range molecules (eq. 2).
4. Bi-cyclic alkanes
R
The alkyl group in the detergent alkylates or the higher alkylbenzenes may cyclize to these higher boiling bi-cyclic alkanes.

The chemical compositions of AB fluids vary significantly depending on the process. There are many other minor components and some of them are strong colored bodies, giving the fluid a deep color.

2. Commercial Products and Manufacturers

In the United States, LABs are manufactured by Condea Vista Company and Huntsman Chemical Corporation with total 1995 production capacity of 840 million lb [9]. Only Vista offers a wide range of AB fluids produced from their LAB plant. The properties of these fluids and comparisons with other fluids are listed in Appendices 1 and 2.

The early BAB-based detergents had poor biodegradability and were replaced quickly by LAB-based detergents. The last BAB producer in the United States, Monsanto, closed down its production in 1991. BABs are still produced in Europe by Chevron and by Exxon Chemical

Copyright © 1999 Marcel Dekker, Inc.

Table 1 1993 Alkylbenzene Base Stock Production Volume, Producers, and Prices

	United States	Western Euorpe	Japan
Volume (metric tons/yr)	3,200	8,100	3,100
Producers:	Vista Chemical Co. Huntsman Chemical Co. Pilot Chemical Co.	Chevron Chemical Co. Exxon Chemical Co. Montedison SpA.	Nippon Oil Co. Idemitsu Kosan Kyodo Oil Co. Showa Shell Sikiyu Cosmo Petrotech Co.
Fluid Type	Estimated price ($/gal)		
Alkylbenzene	1.8–3.3	2.7–3.3	5.5–6.7
PAO	5.8–7.3	5.1	5.8–6.4
Polyol ester	8.2–20	11.1–14.8	10.7–30
Dibasic ester	4.1–13.4	8.4	7.9
PAG	5.6–19	6.8–8.8	5.5–6.7

Company. Both firms offer branched AB fluids of different viscosity grades. The properties of some of these fluids are listed in Appendix 3.

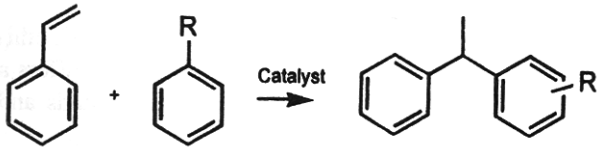
The total volume of alkylbenzene fluids together with all the producers in different regions are summarized in Table 1 [12], which shows the estimated price of alkylbenzene fluids in different regions. The numbers give only the average price of a broad mix of different grades and should not be used on an absolute basis. These numbers consistently point out that AB fluids are lower in price than all other synthetic base fluids, including poly(α-olefins) (PAOs), esters, and polyalkylene glycols (PAGs). This is an advantage for AB fluids, especially when they are used as ester or PAG substitutes.

At this time the total volume for alkylbenzene fluid is very small compared to PAO, esters, or PAG. In the future, if significant demand develops for alkylbenzene fluids, they can move quickly into commercial-scale production because their raw materials are readily available at economical prices and the manufacturing process is well documented [13].

4. Experimental Products and Synthesis

Many experimental alkylbenzene fluids prepared from substituted benzenes are reported in the literature. Some examples are given in the following subsections.

Diphenyl Alkane Fluids These were prepared from styrene or substituted styrene with alkylbenzenes over different types of Friedel–Crafts catalyst (Eq. 7) [11,14–16].



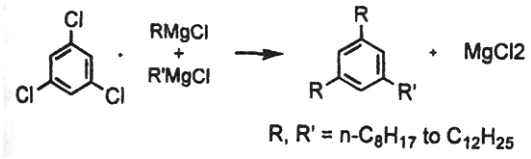
(eq. 7)

The diphenyl alkane fluids were reported to have high traction and good electrical insulating properties.

Copyright © 1999 Marcel Dekker, Inc.

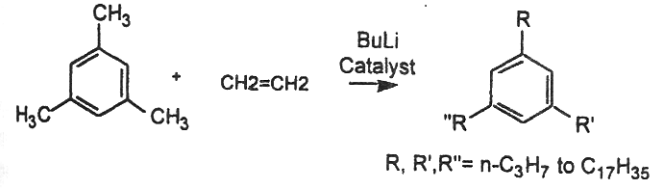
Tri-n-alkylbenzene Fluids Among the several such fluids reported in the literature are the following.

1. 1,3,5-Tri-*n*-alkylbenzene was prepared by reacting 1,3,5-trichlorobenzene with mixed alkyl magnesium chloride (Eq. 8) [17].



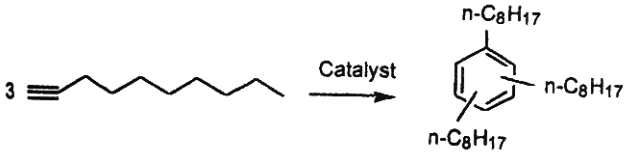
(eq. 8)

2. 1,3,5-Tri-*n*-alkylbenzene was prepared by reacting l,3,5-trimethylbenzene with ethylene over butyllithium catalyst. Alkyl groups having 3–17 carbons with an average of 8 carbons per alkyl group were generated (Eq. 9) [18].



(eq. 9)

3. Mixed 1,3,5- and 1,2,4-tri-*n*-alkylbenzenes with excellent lubricant properties were prepared by cyclotrimerization of 1-alkynes having 8–12 carbons over a solid chromium oxide on silica gel catalyst (Eq. 10) [19].



(eq. 10)

These tri-*n*-alkylbenzenes have excellent viscometrics [low pour points ($< -40°C$) and high viscosity index (VI > 130)] and superior thermal and oxidative stabilities compared to the dialkylbenzenes prepared from Friedel–Crafts alkylation reactions. This is probably because the *n*-alkylbenzenes have fewer alkyl branches at the benzylic position and thus improved thermal and oxidative stabilities.

Dialkylbenzenes of 2–4 cSt Fluids in this viscosity range can be produced from ethylbenzene and α-olefins having 14–18 carbons over a silica–alumina catalyst. This type of AB fluid has VI greater than 95 and pour point less than $-40°C$ [20]. The fully hydrogenated fluids with dialkylcyclohexane structures have higher viscosities and can be used as lubricant base stocks.

Alkylbenzene Fluids Diisopropylbenzene (cumene bottom fraction) and 1-hexadecene over a catalyst of tantalum chloride ($TaCl_5$) on silica gel produced alkylbenzene fluids [21]. The product lubricant had a kinematic viscosity of 3.6 cSt at 100°C and 89 VI. A similar reaction over

Copyright © 1999 Marcel Dekker, Inc.

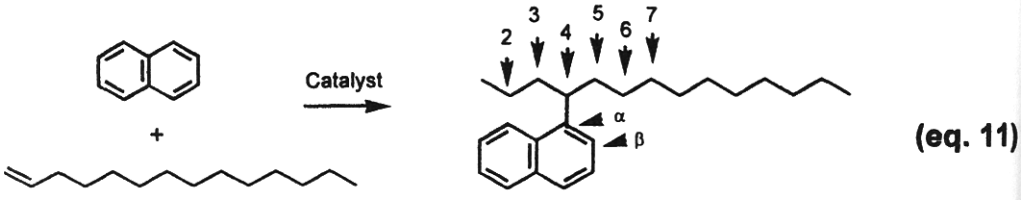
conventional alkylation catalysts (e.g., $A1C1_3$) had a kinematic viscosity of 3.97 cSt at 100°C and 79 VI.

C. Alkylnapthalenes (AN)

Alkylnaphthalene has seen occasional use as a synthetic lubricant base stock since 1930. H. Dressier and others of Koppers Company first reported the high oxidative stability of ANs as lubricant base stocks in 1975 [24]. It is not clear whether Koppers ever commercialized this fluid. Before the 1980s, reports about AN fluids were few [22,23]. Since then, many patents have disclosed the production and use of AN fluids.

On the surface, the chemistry for AN production is quite straightforward: Friedel–Crafts alkylation of naphthalene or substituted naphthalene with olefins, halides, or alcohols should be an easy reaction because naphthalene is highly reactive toward the alkylation reaction. However, numerous patents by Mobil and Nippon Oil indicate otherwise [25–31]. Many of these patents describe the alkylation of naphthalene with large olefins (4–18 carbons) to give an alkylated naphthalene fluid with excellent thermo-oxidative stability and viscometrics. When naphthalene is alkylated with a long chain olefin, the reaction not only produces mono-, di-, and polyalkylated naphthalene, but also many possible isomers for each alkyl substitution, resulting in very complex mixtures. Scheme 4 illustrates the possible product compositions from naphthalene reaction with 1-tetradecene [27].

Scheme IV. Possible alkylnaphthalene compositions.



(eq. 11)

These patents reveal that the AN properties depend on the following factors:

1. The content of monoalkylnaphthalene: higher monoalkylation content results in better thermo-oxidative stability and lower viscosity.
2. α/β ratio: ANs with higher ratio of α to β, or higher α-AN content, has better thermo-oxidative stability.
3. Substitution position of the naphthalene group on the alkyl chain: ANs with more 2-naphthylalkane usually have a higher viscosity index.
4. Tertiary substituted alkylnaphthalenes with no benzylic hydrogen have better thermo-oxidative stabilities than secondary substituted alkylnaphthalenes.
5. AN fluids containing a small amount of alkylated benzo(*b*)thiophene or naphthalenethiol have exceptionally good oxidative stability.

Careful choice of catalysts and reaction conditions can vary the product composition, resulting in many proprietary fluids and process technologies. For example:

1. Zeolite β or modified ultrastable Y (USY) catalysts produce AN with higher α-alkylated naphthalene than acidic clay catalyst.
2. Lower catalyst acidity gives higher α/β ratio. Lower catalyst acidity can be achieved

Copyright © 1999 Marcel Dekker, Inc.

by steaming the catalyst at high temperature, higher SiO_2/Al_2O_3, ratio, or cation exchange, or by selective poisoning of active sites.

3. Mono–secondary AN with α/β ratio greater than 3 can be produced using $FeCl_3$ or $SnCl_4$, catalyst.
4. Mild reaction conditions and mild Friedel–Crafts catalysts ($FeCl_3$, etc.) favor the formation of tertiary alkylnaphthalene over secondary AN.
5. Monoalkylation of naphthalene can be obtained by using a mixed acid catalyst containing methanesulfonic acid and a condensed phosphoric acid [22].

D. Alkylated Aromatics Containing Heteroatoms

In addition to alkylbenzene and alkylnaphthalene, many alkylated aromatics containing oxygen or sulfur atoms have been prepared as synthetic base stocks. However, no large-scale commercial production of these material is known. Among oxygen-containing fluids, alkylated diphenyl ether, benzofuran, and anisole were reported to be excellent synthetic base stocks [32,33,34]. These alkylated aromatics can be produced by the alkylation of diphenyl ether with C_6–C_{18} α-olefins over either conventional Friedel—Crafts catalysts, $A1C1_3$ [35], or solid acidic zeolite catalysts, such as Y-type zeolites [36,37]. Depending on reaction conditions, such as molar ratios of aromatics to olefins or catalyst employed, fluids with different amounts of mono-, di-, or polyalkylated aromatics were produced. Generally, the alkylations take place either ortho or para to the oxygen substituent. Similarly to AN or AB fluids, the oxygen-containing aromatic components can attach to any carbon on the alkyl chain, creating a complex mixture. These subtle structural differences may have an influence on the lubricant performance.

Many S-containing aromatics, including diphenyl sulfide, benzothiophene, thiophene, and phenoxathin, were alkylated to give lube range base stocks over acidic catalysts [36,38–42]. The chemistry for alkylation of S-containing aromatics is similar to that for the oxygen-containing aromatics.

III. PHYSICAL AND CHEMICAL PROPERTIES

A. Alkylbenzene Fluids

1. Viscometrics

Table 2 compares the typical viscometrics of linear alkylbenzene (LAB) and branched alkylbenzene (BAB) fluids, available commercially or reported in the literature, with other common base stocks. The LAB-based fluids usually have VI greater than 100, as well as very low pour points and very good low temperature viscosities. These properties are only slightly different from a typical PAO or dibasic ester. The BAB-based fluids, on the other hand, usually have very poor VI and poor low temperature viscosities.

2. Solvency

The additive solvency of AB fluids is best measured by their respective aniline points (Table 3) [43]. As these data show, AB has a much lower aniline point than PAO or low viscosity mineral oil, indicating better solvency for additives or other polar components in the lubricants [43]. Because of this excellent solvency, AB fluid may be used as an ester substitute in many synthetic industrial or engine oil formulations [44].

3. Volatility

Generally, AB fluids are lower in volatility than mineral oil and higher than PAO fluids of comparable viscosity (Table 4) [43,44]. The alkybenzene fluids produced as detergent alkylate bottoms have a wide distribution of molecular weights because they are produced from olefins in the

Copyright © 1999 Marcel Dekker, Inc.

Table 2 Viscometrics of Alkylbenzene Fluids and Comparable Fluids

Fluid trade name:	V-9050	DN-600[a]	NALKYLENE[a] 600	Zerol 150	Zerol 300			
Company or source:	Vista	Conoco	Conoco	Chevron	Chevron	PAO	Dibasic ester	Mineral oil
Fluid type:	di-LAB	di-LAB	mono-LAB	BAB	BAB	—	—	—
Property								
Viscosity, cSt								
At 100°C	4.3	5.1	1.77	4.35	5.8	3.92	5.3	4.0
At 40°C	22.0	29.1	5.90	33.46	57.0	17.89	28.2	18.9
At −40°C	6,000	8,600	500	NA	NA	2,900	16,100	NA
Viscosity, index	100	115	73	25	14	120	134	97
Pour point, °C	−60	−54	<−68	−40	−35	−68	−59	−15
Average molecular weight	397	—	—	NA	NA	NA	NA	NA
Flash point, °C [b]	215	229	152	170	275	218	235	194
Specific gravity	0.89	0.87	0.87	0.87	0.87	0.82	0.91	0.86

[a] Data from Ref. 3.
[b] Measured by ASTM D-92 or Cleveland open-cup method except V9050 fluid was measured by ASTM D-93 or PM closed-cup method.

Table 3 Comparison of Aniline Points of Base Stocks

	Linear di-AB	PAO	Mineral oil
Viscosity at 100°C, cSt	4.2	3.9	4.0
Aniline point, °C[a]	77.8	116.7	100

[a] By ASTM D-611.

Table 4 Comparisons of Flash Point and NOACK Volatility of Selected AB Fluids[a]

	AB	PAO	100 SUS mineral oil	AB	PAO	200 SUS mineral oil
Viscosity at 100°C, cSt	4.2	3.9	4.0	6.5	6.0	6.2
Noack volatility, wt %	17.3	14.4	27.1	10.8	7.9	10.1
Flash point, °C	215[b]	215[b]	200[b]	230[c]	242[c]	224[c]

[a] SUS, Saybold universal seconds; [b] flash points measured by ASTM D-93 or PM closed-cup method; [c] flash points measured by ASTM D-92 or Cleveland open-cup method.

Copyright © 1999 Marcel Dekker, Inc.

Table 5 Thermal Stabilities of AB Fluids and Other Synthetic Base Stocks

Fluid type	Loss of 38°C viscosity (%)[a]
PAO dimer	75.3
Commercial C_{12}-dialkylbenzene	72.7
1,3,5-Tri-*n*-heptylbenzene	11.2
1,2,4-Tri-*n*-octylbenzene	29.1

[a] At 371°C, N_2 atmosphere, 6 hours, in 304 stainless steel bombs.

range of C_{10}–C_{15}. The lightest fraction of this broad molecular weight distribution contributes significantly to its volatility. If these light ends of the mixed alkylbenzene fluids can be removed by careful distillation, the volatility of AB fluids can be improved. AB fluids generally have flash points similar to those of PAO fluids, another indicator of excellent volatility (Table 4).

4. Thermal and Oxidative Stability

Commercial dialkylbenzene fluids have much better thermal stabilities than esters and are similar in this regard to PAO [18]. Specialty AB fluids such as tri-*n*-alkylbenzene, discussed earlier, have outstanding thermal stability, as tested at 371°C under N_2 (Table 5) [18]. At this testing condition, PAO loses 75% of its viscosity, whereas the tri-*n*-alkylbenzenes lose only 11–29% of their viscosity.

Depending on test conditions, alkylbenzene fluids are comparable to or much better than PAO in oxidative stability (Table 6) [43]. At higher temperature (e.g., 175°C), the AB fluids are similar in oxidative stability to PAO when enhanced with antioxidants [18].

5. Other Properties

AB fluids were reported to have excellent elastomer compatibility, electrical insulating properties, refrigerant compatibility, and lubricity. These unique properties allow the fluids to be used in specialty applications.

B. Alkylnaphthalene

1. Thermal and Oxidative Stability

Early lubricant formulators recognized that lubricants based on alkylnaphthalene fluids had excellent oxidative stability [45]. The electron-rich naphthalene rings in an AN fluid can trap the

Table 6 Comparison of Oxidative Stabilities of Unmodified Base Stocks: AB Versus PAO or Mineral Oil

	Linear di-AB	PAO	100 SUS mineral oil
RBOT, min[a]	23	17	20
Turbine oil oxidative test, hs[b]	109	39	23

[a] RBOT, rotary bomb oxidation test, ASTM D-2272, was conducted at 150°C in the presence of water and copper catalyst under 90 psi of oxygen atmosphere.
[b] ASTM D-943 test was conducted at 95°C in the presence of water and iron–copper catalyst with constant air purge.

Copyright © 1999 Marcel Dekker, Inc.

Table 7 Comparison of Relative Useful Service Life of ANs of Different Chemical Compositions

AN Composition	Viscosity at 40°C (cSt)	Pour point (°C)	α/β Ratio	Service life h[a]
1-octene + naphthalene	10.54	< −45	1.44	88
1-Decene + naphthalene	11.93	< −45	1.33	75
1-Hexadecene + naphthalene	27.03	< −45	1.63	65
1-Octene + naphthalene	—	—	0.28	15
1-Decene + naphthalene	—	—	0.61	18
Diisopropylnaphthalene[b]	—	—	—	2

[a] Oxidation test was conducted at 170°C, oxygen flow rate of 3 L/h in the presence of a copper wire catalyst. Useful lifetime was the time oil reached a total acid number of 1.0 mg KOH/g.

oxy or peroxy radicals generated from hydrocarbon oxidation and thus disrupt the oxidation chain process, preventing oxidative degradation [46,47]. As discussed in Section II C, many patents claim to produce fluids with improved thermol oxidative stabilities by tailoring their molecular structures (Table 7) [28–31]. These data show that the useful service lifetime of AN fluid increases when

the chain length of the alkyl substituent decreases
the α/β ratio of the alkyl substituent increases
the dialkyl AN content decreases

AN fluids with 100°C kinematic viscosities of 4–11 cSt were prepared. These fluids have very low pour point (< −45°C) and good VI (46–118). Other properties of AN, such as seal swelling, lubricity, and additive solvency, are not reported in the literature.

C. Alkylated Aromatics Containing Heteroatoms

The properties of selected alkylated aromatic base stocks containing oxygen or sulfur atoms are summarized in Table 8. In general, these fluids have excellent viscometrics with 100°C viscosi-

Table 8 Physical Properties of Alkylated O- or S-Containing Aromatic Fluids

	Viscosity at 100°C (cSt)	VI	Pour point, (°C)	Ref.
O-containing fluids				
C_{16}-dibenzofuran	7.1	78	−45	33
C_{12}/C_{14}-diphenyl ether	3.6	78	−57	35
di-C_{12}/C_{14}-diphenyl ether	9.7	118	−45	35
C_{14}-phenoxanthin	7.8	41	−35	40
C_{16}-phenoxanthin	7.9	62	−35	40
S-containing fluids				
C_{16}-benzothiophene	5.5	81	−58	41
C_{16}-dibenzothiophene	10.1	4.9	−22	41
C_{16}-thiophene	2.8	129	−13	41
C_{12}-diphenyl sulfide	3.5	90	−53	38
C_{16}-diphenyl sulfide	4.6	135	−43	38

Copyright © 1999 Marcel Dekker, Inc.

ties of 3–10 cSt, good VI, and excellent pour points. They also are claimed to have good thermooxidative stability and lubricity.

VI. APPLICATIONS

Many applications of alkylbenzenes or alkylnaphthalenes were developed to take advantage of their improved lubricating properties, including:

low temperature fluidity and high VI
thermal and oxidative stability
additive solvency
chemical stability (because they are hydrocarbon-only fluids and contain no reactive functional groups)
compatibility with mineral oil and other synthetic fluids (e.g., PAOs, esters)
seal compatibility

A. Early Commercial Applications

In late 1960s, Conoco, a linear alkylbenzene producer at that time, commercialized SAE 5W-20 and 10W-30 engine crankcase oil based on dialkylbenzene base fluid [3,48]. These products had very low pour points ($<-50°F$) and provided satisfactory lubricating function at low temperatures. These early engine oils, introduced in 1969, served the equipment and machinery used during the search for oil in Alaska and Canada and during the construction of trans-Alaska pipeline. Later, these engine oils were claimed to have the advantages of lower oil consumption, better fuel economy, extended drain interval, and excellent engine wear protection. Although the early products claimed many performance features, they were discontinued because they failed to meet overall marketing demand.

In addition to the crankcase oils, several other early synthetic industrial lubricants based on dialkylbenzene fluids were claimed to be useable in low temperature applications. Examples included:

Hydraulic fluids with improved low temperature pumpability and antiwear properties.
A heavy-duty extreme pressure synthetic gear oil with improved low temperature flow property ($-65°F$ pour point). This oil was claimed to improve gear life at low temperature, to provide protection equivalent to a thicker SAE 90 grade gear lubricant, and to provide improved energy-saving features compared to conventional gear oil.
A synthetic grease based on dialkylbenzene and bentonite or lithium soap as thickener. This type of grease was claimed to have good low temperature dispensability, high temperature adhesive properties, and rust inhibiting properties.

The extra cost of synthetic dialkylbenzene fluid compared to conventional mineral oil was considered a disadvantage by early formulators. To reduce cost, producers evaluated semisynthetic lubricants using blends of dialkylbenzene and conventional mineral oil [3]. Based on extensive testing, several of the semisynthetic 5W-30 motor oils were claimed to have the following improvements:

lower oil consumption for the SAE 5W-30 oil
higher oxidative stability by ASTM Sequence III-D test
Lower viscosity change, acid number change, and copper–lead bearing loss by ASTM L-38 single cylinder engine oxidation test
These early synthetic and semisynthetic lubricants failed to reach full-scale commercialization.

Copyright © 1999 Marcel Dekker, Inc.

B. Current Application

1. Alkylbenzenes

The major applications of AB fluids in 1993 are summarized in Table 9 [12]. In 1993 more than 70% of the worldwide alkylbenzene was used as base fluids for synthetic refrigeration lubricants compatible with chlorofluorocarbons (CFCs) or hexachlorofluorocarbons (HCFCs) [49–51]. AB fluids have been used as synthetic substitutes for naphthenic mineral oils in the CFC- or HCFC-compatible refrigeration lubricants for the following reasons:

1. They have excellent low temperature fluidity.
2. Compared to mineral oil or PAOs, either branched or linear alkylbenzenes have much better solubility with HCFC-type refrigerants, such as R22 or R123, at temperatures below −60°C [50].
3. Alkylbenzene fluids have better chemical stability toward the refrigerant than mineral oil because they contain no heteroatoms [51].
4. Their seal compatibility and electrical insulating properties are comparable to those of mineral oil.
5. Alkylbenzenes can be blended with naphthenic mineral oils as semisynthetics to reduce lubricant cost and still maintain some of their performance advantages.
6. Alkylbenzenes have excellent additive solvency to dissolve the antiwear, metal-passivating, and oxidation-inhibiting additive packages used to improve a lubricant's long-term stability.
7. Compared to other synthetic base stocks, such as esters or polyalkylene glycols, AB fluids from the detergent alkylate process are relatively low in cost.

The Montreal Protocol requires the closing of the CFC production by 1996 and the gradual phase-out of HCFC by 2020, to be replaced by the ozone-friendly HFC refrigerant. However, AB fluids have low solubilities in the ozone-friendly HFC refrigerant [12]. This poses a problem for AB because complete solubility of the lubricant fluids in refrigerants is critical for reliable operation in small hermetic refrigeration compressors. As a result, AB fluid may not compete effectively against the alternative refrigeration lubricants based on polyol ester (PE) or polyalkylene glycol (PAG), which are highly soluble in HFC refrigerant. However, PE-or PAG-based lubricants have other performance problems. Recently, many patents and literature claimed these performance deficiencies with PE- or PAG-based lubricants can be improved by using alkylbenzenes or by using blends of alkylbenzenes and PAO mixtures [52–55]. These multicomponent

Table 9 Consumption Rate and Application Areas of AB Fluids in 1993

	Consumption (metric tons/yr)		
	United States	Western Europe	Japan
Refrigeration lubricant	6.8	6.0	—
Metalworking fluid	—	1.2	—
Compressor oil	—	—	2.5
Others	—	—	2.7

Copyright © 1999 Marcel Dekker, Inc.

blends were claimed to have improved lubricity, wear protection, and hydrolytic stability or hydroscopicity, as well as better chemical stability and electrical insulating properties.

Alkylbenzene fluids are used in metalworking fluids. For example, a low viscosity alkylbenzene fluid has shown advantages over highly refined paraffin oil in aluminum cold rolling to produce highly polished aluminum metal surfaces [56]. Alkyl aromatics, including alkylbenzenes, alkylated biphenyls, diphenyl alkanes, and alkylnaphthalene, are used in electrical insulating oil because of their excellent electrical insulating and low water absorption properties [14,57,58].

2. Alkylnaphthalenes

Several recent patents disclose the superior thermal and oxidative stability of AN fluid, and their general use as lubricant base stocks. However, little information is available about actual commercial application of this fluid. Since 1991, Nippon Oil Company has marketed a synthetic lubricant characterized by long drain interval and based on AN fluid for rotary air compressors [59]. This lubricant was formulated to take advantage of the excellent thermal and oxidative stability of the AN fluid. This lubricant extends the oil change interval for rotary air compressors from the conventional 6 months or 1 year to up to 4 years or 12,000 hours of continuous operation. This extended drain interval reduces maintenance work and increases operational reliability.

The use of alkylnaphthalene fluids in high temperature heat transfer fluids [60], in vacuum pump oils [61], and in metalworking fluids [62] has been reported. No specific commercial applications in these areas were clearly documented, however.

3. Alkylated Aromatics Containing Heteroatoms

Many of the specialty alkylated aromatic fluids are known in the patent literature and may have unique properties. However, little information is available about their actual application.

ACKNOWLEDGEMENT

I thank Jane Bitter and Charles Cianci for assistance in the literature search and many of my colleagues, especially Dave Calabro, Dave Baillargeon, and Gary Dudley, for providing valuable comments.

REFERENCES

1. Dressler, H., Alkylated aromatics, in *Synthetic Lubricants and High-Performance Functional Fluids,* 1st ed. (R. L., Shubkin, ed.), Dekker, New York, 1993, pp. 125–144.
2. Koelbel, H., Synthesis of lubricants via the alkylation of naphthalene, *Erdoel Kohle, 1,* 308–318 (1948).
3. Harlacher, E. A., Krenowicz, R. A., and Putnik, C. F., Alkylbenzene based lubricants. Preprint 52D26P, 86th AICHE national meeting, Houston, April 1–5, 1979.
4. Olah, G. A., ed., *Friedel–Crafts and Related Reaction,* Vol. 1, Interscience Publishers, New York, 1963.
5. Olah, G. A., ed. *Friedel–Crafts and Related Reaction,* Vol. 2, part 1, Interscience Publishers, New York, Chap 5. 14, 17, 18.
6. Young, L. B., Preparing phenylalkanes, U.S. Patent 4,301,316, to Mobil Oil Corp. (Nov. 17, 1981).
7. (a) Huss, A., Jr., Le, Q. N., Tabak, S. A., and Wong, S. S., Process for preparing long chain alkyl aromatic compounds employing Lewis acid-promoted amorphous inorganic oxide, U.S. Patent 5,107,048, to Mobil Oil Corp. (April 21, 1992). (b) Le, Q. N., Marler, D. O., McWilliams, J. P.,

Copyright © 1999 Marcel Dekker, Inc.

Rubin, M. K., Shim, J., and Wong, S. S., Process for preparing long chain alkyl aromatic compounds, U.S. Patent 4,962,256, to Mobil Oil Corp. (Oct. 9, 1990).
8. Aufdembrink, B. A., Kresge, C. T., Le, Q. N., Shim, J., and Wong, S. S., Sulfated layered titanium oxide catalysts in process for preparing long chain alkyl aromatic compounds, U.S. Patent 5,105,042, to Mobil Oil Corp. (April 14, 1992).
9. SRI, *Chemical Economic Handbook for Organic Chemicals,* 610.5000, December 1995.
10. Cvengros, J., Faberova, A., and Lazar, L., Low pour point polyalkyl benzene oils for refrigeration compressors, *J Synth. Lubr., 10*(4), 273–284 (1993).
11. Segnitz, A. Hovestadt, A., and Oppenlande, K., Di-phenyl alkane mixture useful as insulating oil, German Potent De 3, 432, 746, to Chem. Fab. Wibarco (March 13, 1986).
12. SRI Specialty Chemicals Update Program, Vol. 7, *Synthetic Lubricants.* Oct. 1997.
13. Berg, R. C, Malloy, T. P., and Vora, B. V., Production of dialkylated aromatics, U.S. Patent 4,520,218, to UPO, Inc. (May 28, 1985).
14. Kawakami, S., Endo, K, Dohi, H., and Sato, A., Electrical insulating oil, European Patent EP 336,133, to Nippon Petro chemicals Co., Ltd. (Oct. 11, 1989).
15. Akatsu, K., Takayama, H., and Matsuoka, T., Di-arylalkane production from styrene and alkylbenzenes over HL-type zeolite catalyst, European Patent EP 421,340, to Kureha Kagaku Kogyo, (April 10, 1991).
16. Aralkylation of alkylbenzenes with styrenes, Japanese Patent J01193232, to Mitsubishi Petrochemical (Aug. 3, 1989).
17. Eapen, K. C, Snyder, C. E., Jr., Gschwender, L., Dua, S. S., and Tamborski, C, Poly-*n*-alkylbenzene compounds. A class of thermally stable and wide liquid range fluids, ACS Petroleum Chemistry preprint, pp. 1053–1058, Philadelphia meeting, Aug. 26–31, 1984.
18. Gschwender, L. J., Snyder, C. E., Jr., and Driscoll, G. L., Alkylbenzenes—Candidate high temperature hydraulic fluids, *J. Soc. Tribol, Lubr, Eng., 46*(6), 377–381 (1990).
19. Wu, M. M., and Ho, S. C, Novel lubricants, U.S. Patent 5,055,626, to Mobil Oil Corp. (Oct. 8, 1991).
20. Bouoher, H. A., Dialkylaromatic and hydrogenated dialkylaromatic synthetic lubricating and specialty oils, European Patent Application EP 0168534 A2, to Exxon Research and Engineering (May 11, 1984).
21. Johnson, T. H., Lubricant composition, U.S. Patent 4,658,072 to Shell Oil Co., (April 14, 1987).
22. Bridwell, B. W., and Johnson, C. E., Mono-alkylation of naphthalene, U.S. Patent 3,959,399, to Nalco Chemical Co. (May 25, 1976).
23. McGuire, S. W., Riddle, J. L., Nicks, G. E., Kerfoot, O. C., and Kennedy, C. D., Preparation of synthetic hydrocarbon lubricants, U.S. Patent 3,909,432, to Continental Oil Co. (Sept. 30, 1975).
24. Dressler, H., and Meilus, A. A., Synthetic oils, U.S. Patent 4,604,491, to Koppers Co. (Aug. 5, 1986).
25. Ashjian, H., Le, Q. N., Marler, D. O., Shim, J., and Wong, S. S., Naphthalene alkylation process, U.S. Patent 5,034,563, to Mobil Oil Corp. (July 23, 1991).
26. Ashjian, H., Le, Q. N., Marler, D. O., Shim, J., and Wong, S. S., Naphthalene alkylation process, WO 91/15443, to Mobil Oil Corp. (Oct. 17, 1991).
27. Le, Q. N., and Shim, J., Catalysts/process to synthesize alkylated naphthalene synthetic fluids with increased alpha/beta isomers for improving product qualities, U.S. Patent 5,177,284, to Mobil Oil Corp. (Jan. 5, 1993).
28. Yoshida, T., and Watanbe, H., Synthetic oils, U.S. Patent 4,714,794, to Nippon Oil Co. Ltd. (Dec. 22, 1987).
29. Yoshida, T., and Watanbe, H., Thermal medium oils, GB 2161176A to Nippon Oil Co. Ltd. (June 25, 1985).
30. Takei, M., Yoshida, T., Nagai, Y., and Masamizu, K., Lubricating oil composition and process for preparing the same, European Patent Application EP 0589107 Al, to Nippon Oil Co. Ltd. (Sept. 24, 1992).
31. Mono-secondary alkylnaphthalene preparation giving specified isomer ratio, Japanese Patent Application JP 01275-536-A, to Nippon Oil Co., Ltd. (Nov. 6, 1989).

Copyright © 1999 Marcel Dekker, Inc.

32. Lubricating oils for high temperature application, Japanese Patent JP 55,073,791, to Matsumura Petroleum Research Laboratory; *Chem. Abstr., 93*:170893 (1980).
33. Rudnick. L. R., Alkylated benzofuran-derived lubricants, U.S. Patent 5,371,248, to Mobil Oil Corp. (Dec. 6, 1994).
34. Sanderson, J. R., and Marquis, E. T., Synthetic lubricant base stocks by co-reaction of olefins and anisole compounds, U.S. Patent 5,202,040, to Texaco Chemical Co. (April 13, 1993).
35. Yamamoto, T., Toyoda, J., and Yagi, T., Study of alkylated diphenyl ethers as synthetic lubricating oil, *J. Jpn Petrol. Inst., 22*(1), 38–43 (1979).
36. Rudnick, L. R., Kremer, R. A., Law, R. A., Naphipur, C. A., and Rowe, C. N., Lubricant adducts and their preparation, WO 9212222A to Mobil Oil Corp. (July 23, 1992).
37. Rudnick, L. R., Kremer, R. A., and Law, D. A., Alkylated diphenyl ether lubricants, U.S. Patent 5,552,071, to Mobil Oil Corp. (Sept. 3, 1996).
38. Kanie, T., and Yamamoto, T., Synthetic lubricating oil, Japanese Patent JP 58,208,392, to Matsumura Sekiyu Research Center (May 28, 1982).
39. Chinlan, G., Tszun'tsze, T., Shumin, K., Tszinchen, C, and Khuifun, L., *Petrol Chem., 32*(2), 141–145 (1992).
40. Rudnick, L. R., Rowe, C. N, Law, D. A., and Naghipur, A. G., Novel alkylated phenoxathin base stock for lubricants, U.S. Patent 5,286,396, to Mobil Oil Corp. (Feb. 15, 1994).
41. Rudnick, L. R., Rowe, C. N., and Law, D. A., Alkylated benzothiophene-derived lubricants, U.S. Patent 5,372,734, to Mobil Oil Corp. (Dec. 13, 1994).
42. Rudnick, L. R., and Rowe, C. N., Alkylated thiophene lubricants, U.S. Patent 5,395,538, to Mobil Oil Corp. (March 7, 1995).
43. Sowle, E. E., and Lachocki, T. M., Linear dialkylbenzenes as synthetic base oils, *J. Soc. of Trib. and Lubr. Eng., 52*(2), 116–120 (1966).
44. Willschke, A., Humbert, D., and Rossi, A., Synthetic base stocks for low viscosity motor oils, *J. Synth. Lubr.,* 5(1), 31 (1988).
45. Nichols, C. W., Jr., and Smith, M. I., Compositions of liquid paraffins containing mixtures of alkyl-substituted polynuclear aromatic hydrocarbons as swelling agents, U.S. Patent 3,498,920, to Mobil Oil Corp. (March 3, 1970).
46. Igarashi, J., Lusztyk, J., and Ingold, K. U., Autoxidation of alkylnaphthalenes. 1. Self-inhibition during the autoxidation of 1-and 2-methylnaphthalenes puts a limit on the maximum possible kinetic chain length, *J. Am. Chem. Soc., 114,* 7719–7726 (1992).
47. Igarashi, J., Jensen, R. K., Lusztyk, J., Korecek, S., and Ingold, K. U., Auto-oxidation of alkylnaphthalenes. 2. Inhibition of the autoxidation of *n*-hexadecane at 160°C, *J. Am. Chem. Soc., 114,* 7727–7736 (1992).
48. Scott, W. P., and McCloud, A. P., Dialkylbenzene-based lubricants for extreme temperature service, *NLGI Spokesman,* November 1977, pp. 260–264.
49. Mead, T. C, and Stein, W. H., Refrigerant and refrigeration oil trends, *Lubrication, 79*(3), (1993).
50. Short, G. D., and Rajewski, T. E., Lubricants for refrigeration and air conditioning, *J. STLE,* p. 270, April 1995.
51. Srinivasan, P., Devotta, S., and Watson, F. A., Thermal stability of Rll, R12B1, R113 and R114 and their compatibility with some lubricating oils, *Chem Eng. Res. Des., 63,* 230–234 (1985).
52. Katafuchi, T., and Nakamura, A., Lubricant for refrigerating machine employing refrigerant comprising tetrafluoroethane, European Patent Application EP 0557796 Al, to Idemitzu Kosan Co. Ltd. (Oct. 2,1993).
53. Sasaki, U., and Suda, S., Refrigerator oil and fluid composition for refrigerator, European Patent Application EP 0693546 Al, to Nippon Oil Co. Ltd. (July 18, 1995).
54. Sasaki, U., and Suda, S., Refrigerator oil and fluid composition for refrigerator European Patent Application EP 0699742 A2, to Nippon Oil Co. Ltd. (Aug. 1, 1995).
55. Glova, D. J., Branched alkylbenzene for refrigerator oil, *U.S.* Patent 4,556,496, to Chevron Research Co. (March 28, 1984).
56. Shido, S., Onodera, K., and Kawanami, T., Influence of chemical structure of base stock on performance of aluminum cold rolling, *Jpn. J. Tribol., 37*(1), 895–905 (1992).

Copyright © 1999 Marcel Dekker, Inc.

57. Sato, A., Endo, K., Kawakami, S., Yanagishita, H., and Hayashi, S., Refined electrical insulating oil and oil-filled electrical appliances, European Patent Application EP 0150252 Al, to Nippon Petrochemicals Co. Ltd. (Dec. 30, 1983).
58. Sato, A., Endo, K., Kawakami, S., Yanagishita, H. and Hayashi, S., Electrical insulating oil comprising mixtures of alkylbenzene fluids, U.S. Patent 4,506,107, to Nippon Petrochemicals Co. Ltd. (March 19, 1985).
59. Takashima, H., Development of long drain rotary air compressor lubricants, in *Proceedings of the International Tribology Conference,* Yokohama, 1995, pp. 899–902.
60. Green, R. L., Larsen, A. H., and Pauls, A. C., Get fluent about heat transfer fluids, *Chem Eng.,* February 1989, pp. 90–98.
61. Magerranmov, M. N., Tsvetkov, O. N., Lyutfaliev, A. G., and Chagina, M. A., Manufacture of vacuum pump oil via alkylation of naphthalene by alpha-olefins, *Khimi Tekhnol Topl. Masel, 4,* 15–16 (1992).
62. Yokoyama, N., and Imai, F., Heat treating oil—comprising mono-alkylnaphthalene with higher secondary or tertiary alkyl groups for quenching and tempering metals, European Patent EP 305,114, to Nippon Oil Co. Ltd. (March 1, 1989).

Appendix 1 Selected Alkylbenzene Fluids Available from Vista Chemical Company and Their Properties

	Fluids			
Properties	7060L-0	7050	160L	3060L-B
Average molecular weight	334	390	370	458
Viscosity, cSt				
At 100°C	3.1	4.1	4.8	6.0
At 40°C	15.6	23.9	29.9	42.1
At −40°C	12,700	22,600	26,400	—
Viscosity index	26	46	82	81
Pour point, °C	−60	−48	−54	−45
Flash point, °C	185	204	210	232
Boiling range, °C				
IBP[a]	340	320	338	171
50%	361	404	359	375
95%	380	470	377	403
Color, ASTM	1.0	≫8.0	1.5	10.5
Appearance	Yellow oily liquid	Dark brown oily liquid	Light brown oily liquid	Dark yellow oily liquid
Dielectric strength, kV	35+	17	47	35+
Aniline point, °C	48	36.2	55.8	75.4

[a] Initial boiling point.

Copyright © 1999 Marcel Dekker, Inc.

Appendix 2 Comparison of Dialkylbenzene from Vista Chemical Company Versus Other Synthetic Base Stocks

	Ratings[a]				
Property	Dialkylbenzene	Olefin oligomers, PAO	Diester	Polyol ester	Mineral oil
Volatility	2	3	2	1	5
Oxidative stability	2	5	4	1	2
Viscosity index (actual)	4 (113)	2 (137)	1 (147)	3 (130)	5 (95)
Pour point (actual), °F	2 (−70)	1 (−90)	1 (−96)	2 (−70)	5 (+5)
Additive solubility	1	5	2	1	1
Sludge-forming tendency	2	2	1	2	5
Seal compatibility	1	3	3	3	1
Cost per gallon	$5	$5	$6	$7	$1

[a]1, best, . . . 5, poorest; or 1, least expensive; 7, most expensive.

Appendix 3 Properties of Zerol Fluids from Chevron Chemical Company

	Zerol number				
Property	55	150	250	350	500
Viscosity, cSt					
At 40°C	5.5	30	46	68	107
At 100°C	1.6	4	5	6	8
Pour point, °C	<−60	−39	−40	−30	−28
Flash point, °C	134	170	190	202	212
Floc point, °C					
R 12	—	<−73	<−73	<−73	<−73
R 22	—	−72	−64	−60	−56
R 502	—	−68	−68	−48	−34

Zerol fluids are produced by Chevron from alkylation of benzene with propylene tetramers. When used as refrigeration lubricant base stock with R12, R22, or R502 refrigerants, Zerol fluids have the following properties: excellent miscibility at low temperature, good oil return, low floc point, good lubricity, excellent compatibility with elastomers.

Copyright © 1999 Marcel Dekker, Inc.